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M E M O R A N D U M

October 27, 1966

TO: P. H. PERMAR
FROM: P. K. SMITH

HIGH TEMPERATURE STABILITY OF THULIUM OXIDE
AND ITS COMPATIBILITY WITH REFRACTORY METALS

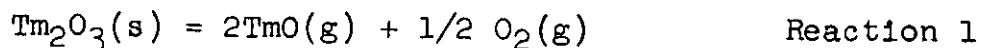
INTRODUCTION

This report presents a theoretical analysis of the vaporization behavior of Tm_2O_3 and its compatibility with potential fuel capsule materials. Thulium-170 is a possible substitute fuel for ^{210}Po in thermionic and Poodle applications. The properties and high-temperature behavior of thulia are being compiled for the Isotopic Data Sheets.

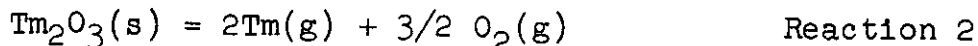
SUMMARY

Thulia appears to be an ideal fuel form for thermionic operation. The only thulium oxide, cubic Tm_2O_3 , has a melting point approaching $2400^\circ C$. Vaporization occurs with constant composition according to the competing

processes:



and



Reaction 2 predominates slightly to produce a total vapor pressure given by

$$\log P_{\text{total}}(\text{atm}) = 7.36 - \frac{31730}{T} \quad (T \text{ in } ^\circ\text{K}).$$

The total vapor pressure calculated from this expression is probably accurate within a range of three decades at 2500°K. Values for $\Delta H_{298^\circ\text{K}}$ for vaporization according to these two reactions are 443 ± 40 kcal/mole and 568 ± 1 kcal/mole, respectively. The boiling point of Tm_2O_3 is estimated to be $4340 \pm 300^\circ\text{K}$. More precise measurement of the vapor pressure can be made in the Knudsen effusion apparatus currently being used at SRL to measure the vaporization rate of curium oxides.

Tm_2O_3 should be compatible with refractory metals and alloys at high temperatures. Thulia should not react with W, Re, or Mo or their alloys even up to its estimated melting point of 2645°K. Appreciable reaction with Ta should only occur above 2000°K in an open capsule. Solid solution ranges for Tm_2O_3 in these metals and vice versa should be small at high temperature. Eutectic melting of Tm_2O_3 and refractory metals or alloy compositions should be near 2000°C.

The decay product of Tm is another rare earth, Yb, which will be present in solid solution with Tm_2O_3 and exhibit nearly identical properties.

DISCUSSION

Two severe limitations of ^{210}Po fuels for use at high temperature are the absence of sufficiently refractory fuel compounds and the extreme pyrophoricity of the fuels presently being considered. Thulium-170, a possible substitute isotope for ^{210}Po , has a nearly ideal fuel compound in Tm_2O_3 . Thulia is extremely high melting, has a very low vapor pressure, and is compatible with refractory alloys at temperatures well over 1920°K , which is the emitter temperature for thermionic diodes. Thulia will not dissolve easily in sea water or react with air to enter life processes if it is exposed in a mission failure. The excellent high-temperature behavior of thulia and some of its properties are described below.

The four most important properties that must be known for design and safety analyses of thermionic heat sources are melting point, thermal conductivity, vapor pressure, and compatibility with refractory metal containers. The vaporization behavior and vapor pressure of Tm_2O_3 have not been determined, but they can be reliably estimated using thermodynamic data available for Tm_2O_3 and similar data for other rare earth oxides. Considerable information on the compatibility of Tm_2O_3 with refractory metals exists or can be inferred from analogous studies in other rare earth systems.

Refractory Properties of Tm_2O_3

Cubic Tm_2O_3 is the only oxide of thulium. It is a "line compound," having a very small range of solid solution at high temperature. Up to 2550°K no structural phase transformations of Tm_2O_3 are known that might cause cracking or degradation of a fabricated fuel form.

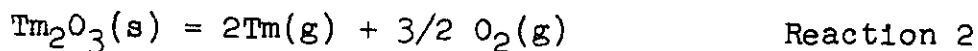
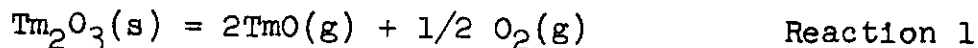
There is some evidence for a transition from cubic to hexagonal symmetry (A-Type RE_2O_3) at 2550°K .⁽¹⁾ Thulia is one of the most stable oxides known, with ΔH_f° at 298°K equal to -451.4 kcal/mole.⁽²⁾ The melting point of Tm_2O_3 has not been measured, but it is estimated to be $2645 \pm 25^\circ\text{K}$ by analogy with the melting temperature of related rare earth oxides.^(1,3)

Vaporization Behavior of Tm_2O_3

The vapor pressure of thulia must be known to evaluate fuel redistribution over long periods of time in thermal gradients and to determine the rate of fuel loss on containment failure because of temperature excursion on burial, shallow trajectory re-entry, or launch pad fire.

In order to measure or calculate vapor pressure, the chemical process by which thulia vaporizes must be established. Thulia must vaporize to a gas of the same composition as the solid (congruent vaporization) because no other stable oxide can be formed by preferential loss of oxygen or metal.

There are several processes to be considered by which Tm_2O_3 may vaporize without change in composition. The principal vaporization process is the congruent vaporization process that develops the highest total pressure at a particular temperature. Of these possible processes two that develop the highest pressures are vaporization to $\text{TmO}(\text{g})$ and vaporization to the elements, according to Reactions 1 and 2.



The magnitude of the pressures developed by these two processes was estimated by the thermodynamic analysis in Appendix I. The equations developed for the total pressure as a function of temperature in the range 0 to 4340°K (boiling point of Tm_2O_3) are:

$$\log P_T(\text{atm}) = 7.78 - \frac{35900}{T} \text{ for Reaction 1,}$$

and

$$\log P_T(\text{atm}) = 7.36 - \frac{31730}{T} \text{ for Reaction 2.}$$

While the errors in P_T are large (a range of three decades), the error difference in P_T for the two processes is small since the estimation errors common to both calculations cancel.

Pressures calculated from these equations are compared at three temperatures in Table I. At each temperature the pressure developed by Reaction 2 is greater than that developed by Reaction 1. Consequently, Reaction 2 represents the predominant vaporization process.

TABLE I
VAPOR PRESSURE OF Tm_2O_3 AT VARIOUS TEMPERATURES

<u>Temperature, °K</u>	<u>Pressure, atm</u>	
	<u>Reaction 1</u>	<u>Reaction 2</u>
2000	6.8×10^{-11}	3.2×10^{-9}
2500	2.6×10^{-7}	4.4×10^{-6}
3000	6.5×10^{-5}	6.0×10^{-4}

Thus, the equation for the total pressure developed by Reaction 2 is the proper expression for the vapor pressure of $\text{Tm}_2\text{O}_3(\text{s})$ and it is accurate within a range of three decades in the pressure at 2500°K.

The data in Table I (and the corresponding equations) are shown graphically in Figure 1 as typical Clausius-Clapeyron plots. If Reactions 1 and 2 are written so that each produces one total mole of gas, as they are in Figure 1, then the entropy change for both reactions should be about the same. Under this condition, the predominant reaction (the one that requires the least free energy to make a mole of gas) will be the reaction with the smallest heat of vaporization. Figure 1 shows that Reaction 2 does predominate. While the vapor pressure developed by Reaction 2 is higher, the pressure for Reaction 1 approaches the pressure for Reaction 2 at very high temperature, because the heat of vaporization for Reaction 1 is larger. The standard heats of vaporization at 298°K per mole of Tm_2O_3 calculated from the data in Appendix I are 443 ± 40 kcal/mole and 568 ± 1 kcal/mole for Reactions 1 and 2, respectively.

These curves are applicable up to the boiling point of Tm_2O_3 . The boiling point was estimated from the temperature at which the vapor pressure equals 1 atm to be $4340^\circ\text{K} \pm 300$, which agrees with measured boiling points of other RE_2O_3 compounds near 4200°K .⁽³⁾

White, Walsh, Ames, and Goldstein determined the vaporization process for several rare earth oxides, using mass spectrometric techniques to identify the relative importance of $\text{MO}_2(\text{g})$, $\text{MO}(\text{g})$, and $\text{M}(\text{g})$.⁽⁴⁾ They found that the lighter rare earth sesquioxides vaporize congruently principally by Reaction 1. As atomic number increases, Reaction 2 becomes more important. The contribution of $\text{MO}_2(\text{g})$ to the vapor pressure is negligible.

Similar experiments on other RE_2O_3 compounds by Panish⁽⁵⁾ supported these observations. Panish estimated from measurements of mass spectrometer ion currents that the partial pressure of $\text{Tm}(\text{g})$ over Tm_2O_3 is about

10^{-6} atm at 2300°K and that P_{Tm}/P_{TmO} is between 10 and 20. These observations are in excellent agreement with the values of P_{Tm} at 2300°K of 3×10^{-7} atm and P_{Tm}/P_{TmO} of 13, calculated from Equations 2 and 4.

If the fuel capsule were to develop a leak and continue to operate at 2300°K or higher, the weight of Tm_2O_3 fuel that might be lost from a fuel capsule over a long period of exposure would be small. The maximum loss can be calculated from the equation,

$$P_T = \frac{W}{a \cdot 44.3} \sqrt{\frac{T}{M}},$$

where W is the weight loss, a is the area of the leak, t is the time, and M is the average molecular weight of the gas.

For example, only about 5 mg of Tm_2O_3 would be lost through a pinhole leak of 10^{-4} cm² in six months at 2300°K. The error in the weight loss calculated from this equation is directly proportional to the error in P_T . If a more accurate estimate of the fuel loss than can be calculated from the expressions for P_T given in Equation 4 of the Appendix is needed, the vapor pressure must be measured. The Knudsen effusion apparatus, already operating in the Actinide Materials Facility to measure the vaporization rate of curium oxide, can be used to measure the vaporization rate and vapor pressure of Tm_2O_3 easily to 10% and, with more care, to 3%. If interest in ^{170}Tm increases and more accurate vapor pressure data are needed, these measurements will be made.

Compatibility of Tm_2O_3 With Refractory Metals

Reduction by Refractory Metals

Thulia should be compatible with W, Mo, and Re and their alloys even above its melting temperature, and with Ta up to 2300°K. Thus, from a

materials viewpoint, thulia may be ideally suited for operation as a heat source for thermionic or Poodle devices. Simple reactions of these metals with Tm_2O_3 to form Tm liquid and refractory metal oxides cannot occur because of the very high stability of Tm_2O_3 compared to the stability of the refractory metal oxides.

Reduction reactions with Ta, Mo, or W to form binary alloys and refractory metal oxides probably will not occur because thulium does not form binary compounds or extensive solid solutions with any of these refractory metals. Moriarity and Baenziger⁽⁶⁾ found no intermediate compounds between W, Mo, or Ta and Gd or Dy and limited mutual solubility. Daane and Spedding⁽⁷⁾ report less than 0.2 wt % Mo is soluble in Ce or La at 1570°K and find no intermediate phases. Spedding and Daane^(8,9) found that no Ta-Tm compounds exist and that Tm will dissolve 1.5 wt % Ta to raise the melting point of Tm by 135° to 1950°K.

The reaction of Tm_2O_3 with Re to form $TmRe_2$ is possible if $TmRe_2$ is sufficiently stable. The existence of $TmRe_2$ seems certain since Lundin⁽¹⁰⁾ has found YRe_2 , which melts at 2790°K. However, Foex and Traverse⁽¹⁾ have melted Tm_2O_3 on rhenium filaments in high temperature X-ray experiments with no visual reaction observed or unexpected changes in X-ray patterns.

Eutectic Melting

Melting of the eutectic composition formed between Tm_2O_3 and the refractory metal container would increase surface contact to enhance diffusion and would lead to fuel redistribution. But the eutectic temperatures for Tm_2O_3 and pure refractory metals systems are expected to be well over

2250°K. For example, the eutectic temperature for Y_2O_3 -W is about 2405°K, which is 285° less than the melting point of Y_2O_3 . No eutectic melting was reported by Hoyt, Cummings, Zimmerman and Perrine⁽¹¹⁾ at 2270°K between W and Dy_2O_3 , Sm_2O_3 or Eu_2O_3 (with melting points of 2610, 2595, and 2320°K, respectively). Eutectic temperatures between refractory metal alloys and Tm_2O_3 will be lower than for the corresponding systems, Tm_2O_3 -pure metals, but are expected to be near 2300°K.

Formation of Ternary Compounds

Reactions of Tm_2O_3 with the refractory metals and alloys to form ternary compounds or extensive solid solutions probably do not occur. No ternary oxides are known to exist whose stoichiometry can be represented by a stoichiometric combination of Tm_2O_3 and refractory metal. Some ternary compounds do exist, e.g., tungstates, molybdates, and tantalates, but they are oxygen-rich compared to the system Tm_2O_3 -M.

Walsh, Goldstein and White⁽¹²⁾ found that La_2O_3 and Nd_2O_3 react appreciably with Ta crucibles above 2000°K to produce vapor pressures of $LaO(g)$ or $NdO(g)$ that are comparable to the vapor pressure observed at temperatures 200 to 300° higher in inert crucibles, according to the reaction $3 RE_2O_3 + Ta = 5REO(g) + RETaO_4$. Similar behavior would occur between Ta and Tm_2O_3 in an open system. In a closed capsule with no temperature gradients, tantalum will not reduce Tm_2O_3 or form $TmTaO_4$ even above the melting point of Tm_2O_3 , since rapid achievement of the equilibrium pressure of $TmO(g)$ would prevent the reaction from continuing.

Vapor Transport Reactions

The formation of small amounts of refractory metal oxide gas by limited reaction between thulia and the container metal at high temperatures presents the possibility of vapor transport erosion of capsule metal in a temperature gradient. This mechanism for incompatibility has been evaluated for tantalum transport, since tantalum is the refractory metal most likely to show such an effect.

Temperature gradients in a capsule should not cause a tantalum capsule to be eroded from the inside even though TaO(g) is very stable and has a fairly high vapor pressure at temperatures over 2000°K . Possible transport processes involving TaO(g) are all endothermic and could transport Ta only to cold surfaces where it exists initially anyway. Compatibility failure because of vapor transport in a temperature gradient is even less probable for Mo, W and Re since their gaseous oxides are much less stable than TaO(g) .

Experimental Confirmation of Compatibility

The compatibility of Tm_2O_3 and other rare earth sesquioxides with W, Mo, Re, Ta, and Nb has been demonstrated in several experiments. Thulia has been heated to 2550°K in experiments of the order of hours of exposure on W and Re filaments by Foex⁽¹⁾ and to 2270°K on W and Mo filaments at SRL by W. C. Mosley in high temperature X-ray diffraction experiments. No reaction was observed either visually or by unexpected changes in X-ray pattern. Grossman⁽¹³⁾ has cycled yttrium sesquioxide in a tungsten crucible through the melting point and observed only small

solubility effects of W in Y_2O_3 and vice versa. Several researchers^(12,14) have used tungsten effusion cells to study the vaporization behavior of RE_2O_3 , including Tm_2O_3 , and found no reaction with tungsten. Hoyt, et al,⁽¹¹⁾ have studied the compatibility of Dy_2O_3 , Sm_2O_3 , and Eu_2O_3 with Mo, W, and Nb by heating powdered materials in vacuum for 2 hr at 2070-2270°K and subsequently examining the product metallographically; no signs of reaction were observed between any pair of oxide and metal.

A thulia wafer has been heated in a welded tantalum container at 2200°K for 24 hr at SRL by J. R. Keski with no reaction observed metallographically or by X-ray diffraction analysis. Reaction between Ta and Tm_2O_3 was observed in 1 hr at 2170°K under conditions where $TmO(g)$ was removed by flowing helium.

Influence of Yb Decay Product

Thulia has the unique property of forming a decay product, ytterbium, that is almost identical in refractory character, composition, and structure with its parent. The ytterbium will form a solid solution with Tm_2O_3 as $Tm_{2-x}Yb_xO_3$, and the high temperature behavior, stability, and compatibility of this solid solution will be nearly identical to Tm_2O_3 .

APPENDIX ITHERMODYNAMIC ANALYSIS OF VAPORIZATION OF Tm_2O_3 Vaporization by Reaction 1

From the Third Law of thermodynamics and the equilibrium constant for Reaction 1, the standard free energy change at temperature is given by

$$\Delta G_T^\circ = \Delta H_T^\circ - T\Delta S_T^\circ = -RT \ln K = -RT \ln P_{TmO}^2 P_{O_2}^{1/2}.$$

From the stoichiometry for Reaction 1, the partial pressures of the gases are related by $P_{O_2} = 1/4 P_{TmO}$, which when substituted into the free energy expression above gives

$$\Delta H_T^\circ - T\Delta S_T^\circ = -RT \ln P_{TmO}^2 (1/4 P_{TmO})^{1/2} = -RT \ln 1/2 P_{TmO}^{5/2}.$$

The total pressure is related to the partial pressures by

$$P_{Total} = P_T = P_{TmO} + P_{O_2} = P_{TmO} + 1/4 P_{TmO} = 5/4 P_{TmO};$$

so that

$$\Delta H_T^\circ - T\Delta S_T^\circ = -RT \ln 1/2 (4/5 P_T)^{5/2} = -RT \left[\ln 1/2 (4/5)^{5/2} + \ln P_T^{5/2} \right].$$

Rearranging and solving for $\log_{10} P_T$ produces Equation 1.

$$\log P_T(\text{atm}) = \frac{2}{(5)(4.576)T} (T\Delta S_T^\circ - \Delta H_T^\circ - 4.576T \log 0.3) \quad \text{Equation 1}$$

The standard heat of vaporization (ΔH_T°) and the standard entropy change (ΔS_T°) for the vaporization at a particular temperature are evaluated from the following equations:

$$\Delta H_T^\circ = \underbrace{\left[2 -D^\circ(TmO) + \Delta H_{\text{vap}}^\circ(Tm) + 1/2 D^\circ(O_2) \right]}_{\Delta H_f^\circ(TmO(g))} + 2 \left[TS_T^\circ + T \left(\frac{F_T^\circ}{T} - \frac{H^\circ}{T} \right) \right] TmO$$

(cont'd)

(cont'd)

$$+ 1/2(H_T^\circ - H_o^\circ)_{O_2} - \Delta H_{f298}^\circ(Tm_2O_3) - (H_T^\circ - H_{f298}^\circ)_{Tm_2O_3}$$

$$\Delta S_T^\circ = 2S_T^\circ(TmO) + 1/2 S_T^\circ(O_2) - S_T^\circ(Tm_2O_3)$$

The significance of these terms and their calculated or estimated values at 2500°K are described below:

ΔH_{2500}° for Reaction 1

$D_o^\circ(TmO)$ = standard dissociation energy at 0°K for the decomposition of $TmO(g)$ into gaseous atoms = 122 ± 20 kcal/mole from Figure 2⁽⁴⁾

$\Delta H_{vap}^\circ(Tm)$ = standard heat of vaporization of thulium at 0°K = 58.4 kcal/mole⁽¹³⁾

$1/2D_o^\circ(O_2)$ = standard dissociation energy at 0°K of $O_2(g)$ into gaseous atoms = 60.5 kcal/mole⁽¹⁵⁾

The standard heat of formation of $TmO(g)$ at 298°K calculated from the above terms is assumed to be the same as that calculated at 0°K.

$S_T^\circ(TmO)$ = entropy of $TmO(g)$ at 2500°K = 76 ± 2 eu, estimated⁽⁴⁾

$(\frac{F_T^\circ - H_o^\circ}{T})_{TmO}$ = free energy function to extrapolate energy of $TmO(g)$ from 0 to 2500°K = 67 ± 2 eu, estimated⁽⁴⁾

$(H_T^\circ - H_o^\circ)_{O_2}$ = difference in heat content of $O_2(g)$ between 0 and 2500°K = 11.0 kcal/mole⁽¹⁵⁾

$\Delta H_{f298}^\circ(Tm_2O_3)$ = standard heat of formation of $Tm_2O_3(s)$ at 298°K = -451.4 kcal/mole⁽²⁾

$(H_T^\circ - H_{298}^\circ)_{\text{Tm}_2\text{O}_3}$ = difference in heat content of $\text{Tm}_2\text{O}_3(\text{s})$ between 298 and 2500°K = 84.6 ± 15 kcal/mole, estimated from Figure 3⁽¹⁶⁾

The standard heat of vaporization calculated from the above data is $\Delta H_{2500}^\circ = 411 \pm 75$ kcal/mole at 2500°K. The uncertainty is the combination of uncertainties in the component terms, which were liberally assigned.

ΔS_{2500}° for Reaction 1

$$\begin{aligned} S_T^\circ(\text{TmO}) &= 76 \pm 2 \text{ eu, estimated}^{(4)} \\ S_T^\circ(\text{O}_2) &= \text{standard entropy of } \text{O}_2(\text{g}) \text{ at } 2500^\circ\text{K} = 66.3 \text{ eu}^{(15)} \\ S_T^\circ(\text{Tm}_2\text{O}_3) &= \text{standard entropy of } \text{Tm}_2\text{O}_3(\text{s}) \text{ at } 2500^\circ\text{K} = 98 \pm 10 \text{ eu}^{(4)} \end{aligned}$$

The standard entropy change for the vaporization at 2500°K is $\Delta S_{2500}^\circ = 89 \pm 14$ eu.

The final expression for total pressure as a function of temperature according to Reaction 1 is obtained by substituting ΔH_{2500}° and ΔS_{2500}° in Equation 1.

$$\log P_T(\text{atm}) = 7.78 - \frac{35900}{T} \quad \text{Equation 2}$$

for temperatures between 0 and 4340°K (assuming ΔC_p° equals 0 over the temperature range). The uncertainty in P_T at 2500°K, arising from a combination of the uncertainty of estimation in ΔH_{2500}° and ΔS_{2500}° is over a range of four decades. The uncertainty in P_T changes with temperature, but the magnitude at 2500°K is typical of the quality of the data.

Vaporization by Reaction 2

The free energy relation for Reaction 2, corresponding to that derived above for Reaction 1, is $\Delta F_T^\circ = \Delta H_T^\circ - T\Delta S_T^\circ = -RT \ln P_{Tm}^2 P_{O_2}^{3/2}$.

From the stoichiometry, the partial pressures are related by

$$P_{O_2} = 3/4 P_{Tm}; \text{ and the total pressure is given by}$$

$$P_T = P_{Tm} + P_{O_2} = P_{Tm} + 3/4 P_{Tm} = 7/4 P_{Tm}.$$

Substitution into the free energy expression above produces

$$\Delta H_T^\circ - T\Delta S_T^\circ = -RT \left[\ln(3/4)^{3/2} (4/7)^{7/2} + \ln P_T^{7/2} \right]$$

Again, rearranging and solving for $\log P_T$ produces Equation 3.

$$\log P_T(\text{atm}) = \frac{2}{(7)(4.576)T} (T\Delta S_T^\circ - \Delta H_T^\circ - 4.576 T \log 0.0915)$$

Equation 3

The component terms to calculate ΔH_T° and ΔS_T° are given below. Most of the quantities were calculated or estimated for Equation 1 above.

$$\begin{aligned} \Delta H_T^\circ = & 2\Delta H_{298, \text{vap}}^\circ(Tm) + 2(H_T^\circ - H_{298}^\circ)_{Tm(g)} + 3/2(H_T^\circ - H_{298}^\circ)_{O_2} \\ & - \Delta H_{f, 298}^\circ(Tm_2O_3) - (H_T^\circ - H_{298}^\circ)_{Tm_2O_3} \end{aligned}$$

$$\Delta S_T^\circ = 2S_T^\circ(Tm(g)) + 3/2S_T^\circ(O_2) - S_T^\circ(Tm_2O_3)$$

 ΔH_{2500}° for Reaction 2

$$(H_T^\circ - H_{298}^\circ)_{Tm(g)} = \text{difference in heat content for } Tm(g) \text{ between } 298 \text{ and } 2500^\circ K = 12.2 \pm 1.0 \text{ kcal/mole from Figure 4}^{(4)}$$

The standard heat of vaporization at $2500^\circ K$ is

$$\Delta H_{2500}^\circ = 524.5 \pm 17 \text{ kcal/mole.}$$

ΔS°_{2500} for Reaction 2

$S^\circ_T(\text{Tm(g)})$ = standard entropy of Tm(g) at 2500°K = 56 ± 2 eu,
estimated⁽⁴⁾

The standard entropy of vaporization at 2500°K is ΔS°_{2500}
= 113 ± 14 eu.

Equation 4 is the derived relation between P_T and T obtained by substituting ΔH°_{2500} and ΔS°_{2500} into Equation 3.

$$\log P_T(\text{atm}) = 7.36 - \frac{31730}{T} \quad \text{Equation 4}$$

for all temperatures between 0 and 4340°K, again assuming $\Delta C_p = 0$ at all temperatures. An uncertainty within a range of three decades in the total pressure arises from the uncertainty of estimation in ΔH°_{2500} and ΔS°_{2500} in Equation 4.

PKS:sm

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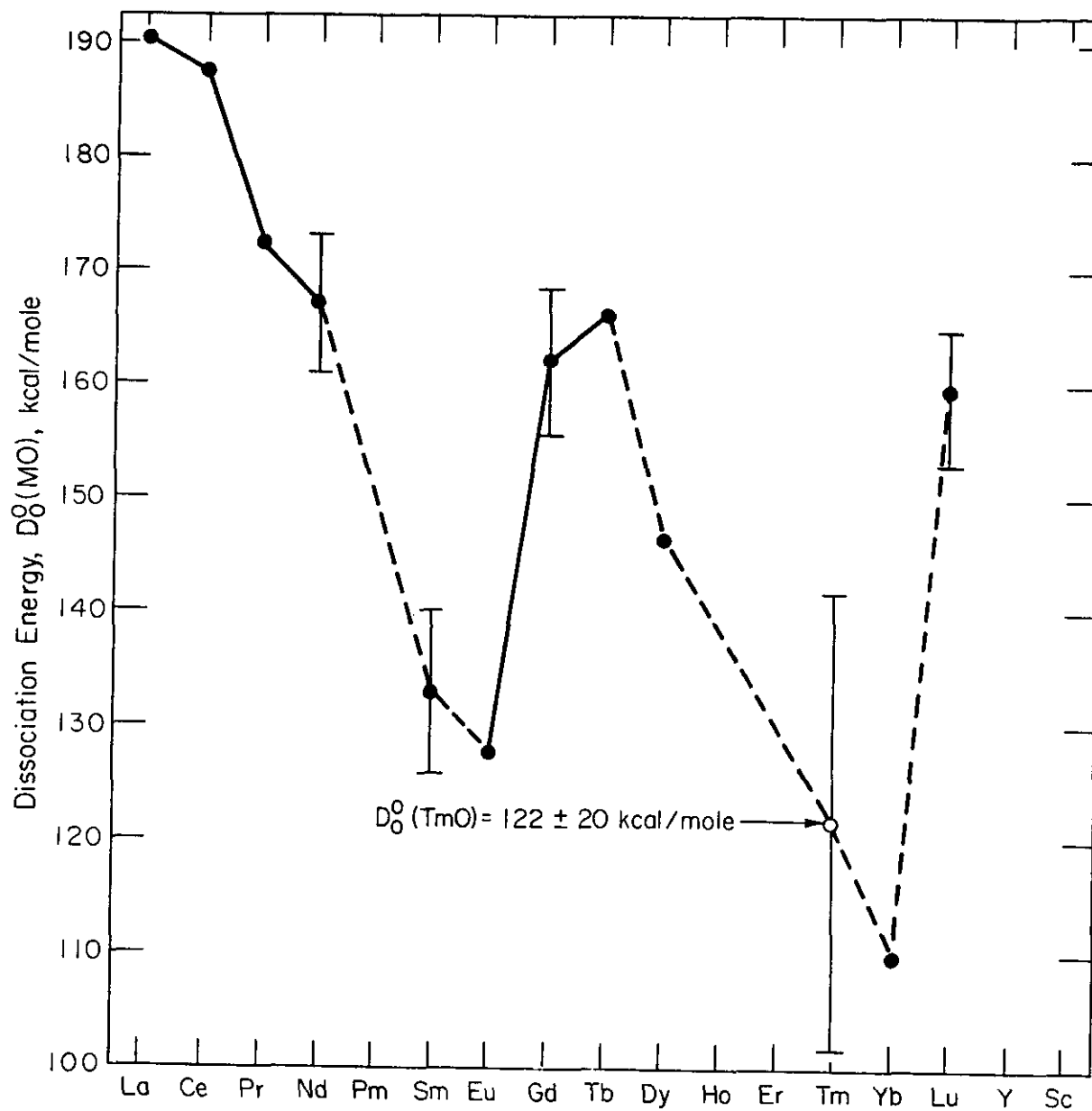


Figure 1. Total Pressure for Congruent Vaporization of Tm_2O_3

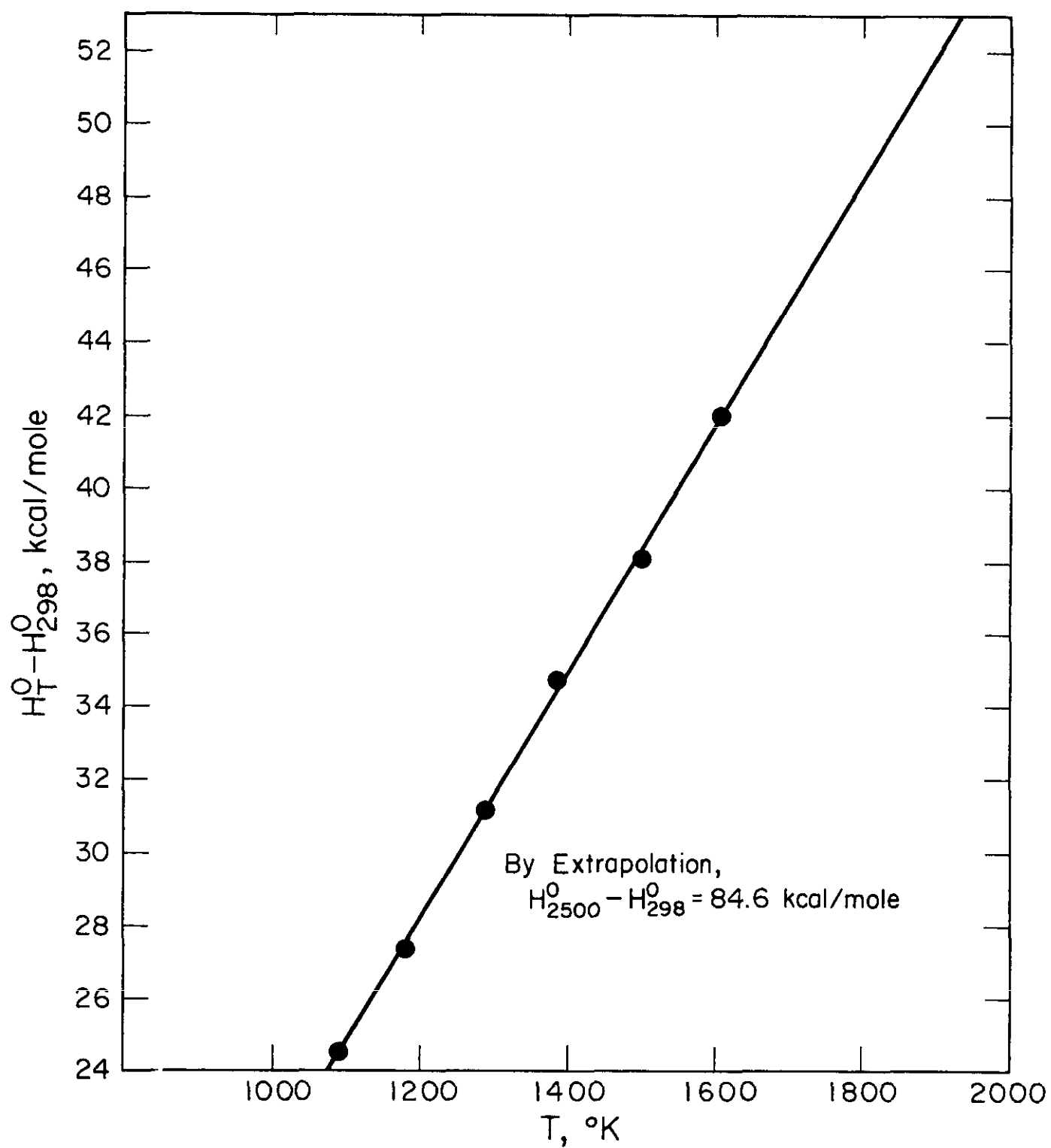


Figure 2. Dissociation Energy for Rare Earth Monoxide Molecules⁽⁴⁾

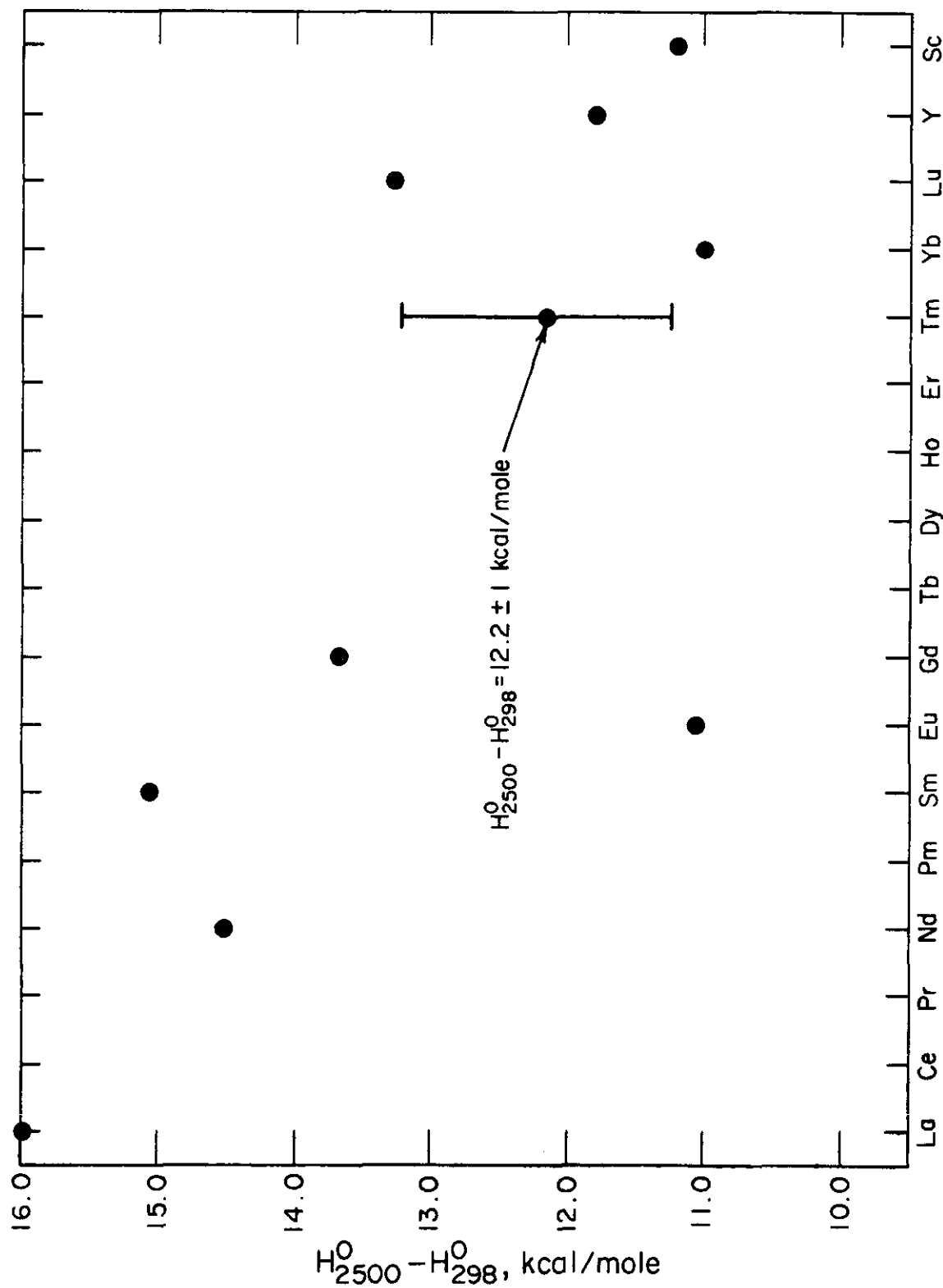


Figure 3. Change in Enthalpy of Tm_2O_3 With Temperature ⁽¹⁶⁾

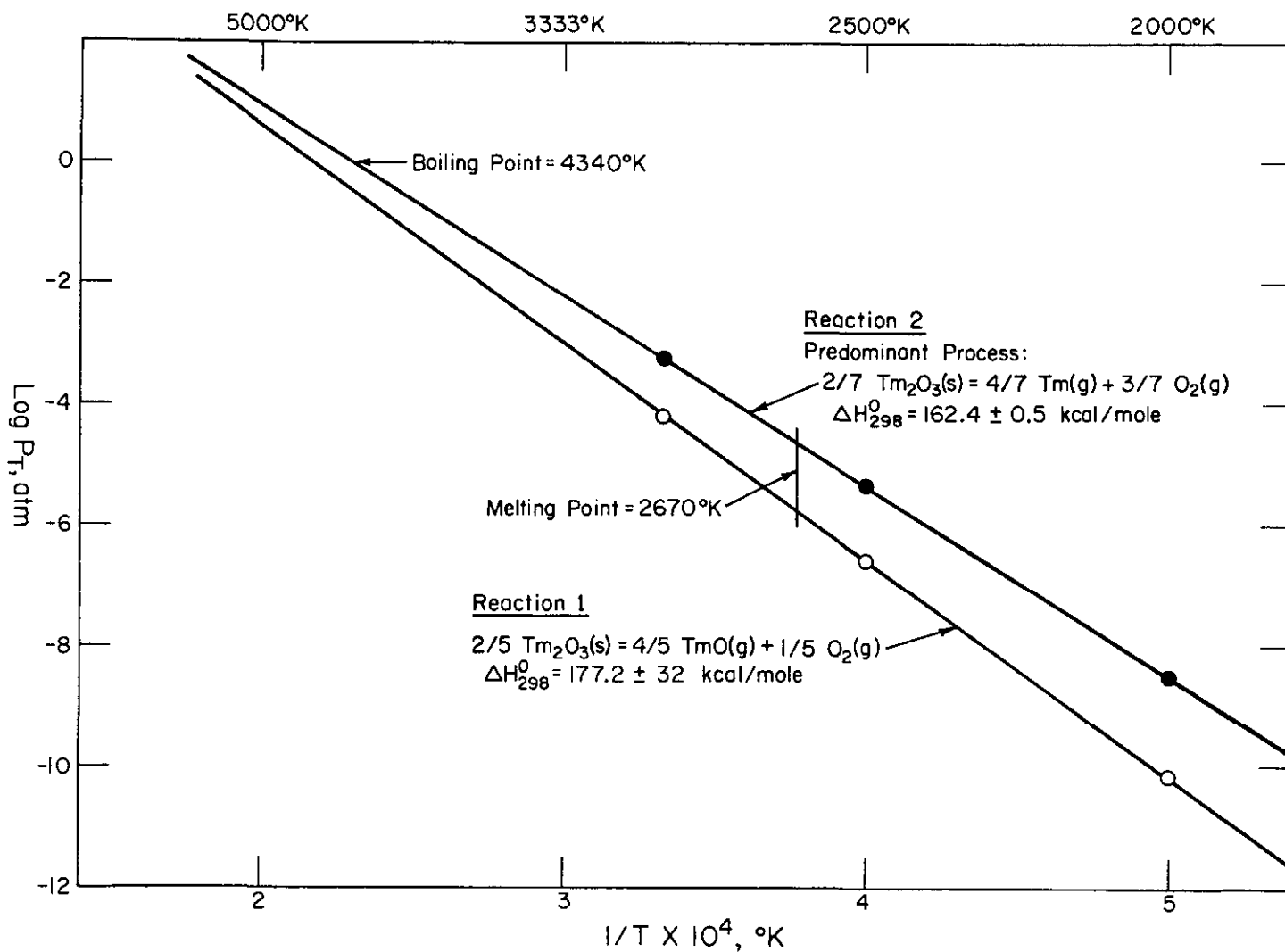


Figure 4. Enthalpy of Rare Earth Vapor at 2500°K.